

MICROSTRUCTURE AND STRESS ANALYSIS OF THE
MULLEN CREEK - NASH FORK SHEAR ZONE, WYOMING

by

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INTRODUCTION

The microstructure of quartz in rocks from the Mullen Creek-Nash Fork shear zone in southeastern Wyoming has been used to characterize the deformation, and to determine the paleostress distribution across the shear zone. Recent studies have shown that, in minerals which have been plastically deformed at constant stress, three microstructural parameters, grain size, subgrain size, and dislocation density, are directly related to the magnitude of the differential stress. These microstructural parameters depend on temperature and strain rate only as the stress, temperature and strain rate are related through a flow law. The relationships between stress and microstructural parameters have been determined for ceramic materials and metals (Takeuchi and Argon, 1976), olivine (Kohlstedt et al., 1976; Durham et al., 1977; Mercier et al., 1977; Raleigh and Kirby, 1970; Post, 1977), calcite (Briegel and Goetze, 1978; Goetze and Kohlstedt, 1977; Schmid et al., 1977), and quartz (McCormick, 1977; Durham et al., 1977; Mercier et al., 1977).

Most studies of the relationships between microstructure and stress have utilized olivine crystals or olivine-rich rocks. Mercier et al. (1977), utilized these studies in a study of suites of xenoliths from basalts and kimberlites to determine stress as a function of depth in the mantle. They found that the differential stress is approximately 300 bars at 500 km and 30 bars at 100 km. Goetze (1975) analyzed sheared nodules from Lesotho kimberlites, southeast Africa and determined that fine-grained nodules had experienced a differential stress of 2 to 3 kbar upon ascent. Unfortunately, olivine-bearing rocks associated with shear zones have usually been serpentinized to the extent that they can not be used for stress determinations. Recently, McCormick (1977) has characterized the relationship between dislocation density and stress for quartz by experimentally deforming synthetic quartz crystals. Twiss (1977) summarized most of the information relating subgrain size and dynamically recrystallized grain size to differential stress during steady-state creep, for olivine and quartz. Mercier et al. (1977) found that the grain size, A , is related to the differential stress by $A = 6.6\sigma^{-1.4}$, for wet quartzites. This recent work on quartz and quartzites is particularly important to the study of differential stress distributions across faults because quartz is common in plastically deformed rocks from deeply eroded shear zones.

Recently, there have been several attempts to estimate the tectonic differential stress of faults using dislocation density and recrystallized grain size data. Briegel and Goetze (1978) calculated a paleostress of 2 kbar at the base of the Glarus overthrust in Switzerland, based on the dislocation densities in fine-grained Lochseitenkalk. Burg and Laurent (1978) estimated a paleo-differential stress of 0.5 kbar across a shear zone in a granodiorite from the Massif Central, based on dislocation densities. Their estimate of the differential stress, based on subgrain size, was 1.5 kbar in the shear zone and 0.25 kbar in the unsheared granodiorite. Twiss (1977)

estimated, from recrystallized grain size, the tectonic differential stresses across several thrust faults, including the Moine thrust in Scotland, the Arltunga Nappe Complex in central Australia and the Woodroffe thrust in central Australia, to be between 0.5 and 2.0 kbar. Weathers et al. (1979) have estimated the paleo-differential stress to have been 1.5 to 2.0 kbar along the Moine thrust, from recrystallized grain size and dislocation densities.

We report here our preliminary analysis of the microstructures in quartz-bearing rocks from the Mullen Creek - Nash Fork shear zone which is part of a northeasterly trending belt of Precambrian faults in western Colorado and southeastern Wyoming, and could be a deeply eroded analog of the San Andreas system (Warner, 1978).

GEOLOGY AND TECTONIC SETTING OF THE MULLEN CREEK - NASH FORK SHEAR ZONE

The Medicine Bow Mountains of southeastern Wyoming are uplifted Precambrian rocks which form the core of a large, asymmetric anticline. The Mullen Creek - Nash Fork shear zone crosses the central region of the Medicine Bow range, dividing it into northwestern and southeastern halves. The shear zone has been traced for approximately 40 km, trending northeasterly and varying in width from approximately 0.75 km in the southwest, to 5 km in the northeast (see Houston, 1968; Figure 1).

The Mullen Creek - Nash Fork shear zone divides the central Medicine Bow range into two regions of substantially different lithology and structure (Houston, 1968). Northwest of the shear zone the Precambrian rocks consist of quartz-feldspar gneiss overlain by metasedimentary rocks. The quartz-feldspar gneiss includes hornblende gneiss, augen gneiss and biotite gneiss. Whole-rock Rb-Sr ages of the biotite gneiss are 2.4 b.y. (Hills et al., 1968). Most of the Precambrian rocks of the region have been metamorphosed to garnet amphibolite facies (Houston, 1968). It is estimated that the Medicine Bow Mountains have been eroded 15 to 25 km. Rocks presently exposed at the surface were originally deformed under conditions of plastic flow.

The metasedimentary rocks north of the shear zone include rocks of the Deep Lake Formation and the Libby Group. Both units are Precambrian in age. The Deep Lake Formation outcrops mostly in the northern regions of the Medicine Bow Mountains and includes several quartzites, a metabasalt, an amphibolite, marble, chlorite schist, and a thick metaconglomerate. The Deep Lake Formation includes the oldest metasedimentary rocks of the region. Rocks of the Libby Creek Group outcrop extensively along the western margin of the shear zone (Figure 1). The Libby Creek Group includes eight formations, comprised of quartzite, schist, slate and metadolomite. Several sections were measured and sampled in the quartzites of the Libby Creek Group for this study.

Our preliminary work on the deformation-induced microstructures of rocks from the Mullen Creek - Nash Fork shear zone was done on the Medicine Peak Quartzite. This quartzite unit attains a maximum thickness of approximately 2000 meters in the Medicine Bow Mountains. The quartzite varies from coarse-grained kyanitic quartzite in its lower half, to a finer-grained, white quartzite in its upper half. The kyanitic quartzite, varying from blue to dark green, has an average composition of 83% quartz, 10% kyanite and 4% muscovite (Houston, 1968). The upper half of the quartzite unit includes thin beds of conglomerate and has an average composition of 88% quartz, 6% muscovite and 5% opaque minerals including magnetite and hematite. Our collections of the Medicine Peak Quartzite were made in the region between North Mullen Creek and South French Creek in the lower, kyanitic quartzite.

Recently, it has been suggested that the Mullen Creek - Nash Fork shear zone marks the northern margin of a belt of Precambrian faults which may be analogous to the San Andreas fault system (Warner, 1978). This belt of shear zones, called the Colorado Lineament by Warner, extends approximately 1000 km, from Wyoming through Colorado to the Grand Canyon region of Arizona. The Colorado Lineament may have a northeastern extension in the Precambrian terrain of Minnesota and southern Canada (Warner, 1978; Dutch, 1979). The various shear zones within the Colorado Lineament were active beginning 1.5 to 2.0 b.y. ago (Warner, 1978). Many of the individual faults were reactivated during the Laramide orogeny, producing complex deformational histories for the rocks associated with many of the shear zones (Tweto and Sims, 1963).

PETROGRAPHY OF ROCKS FROM THE MULLEN CREEK - NASH FORK SHEAR ZONE

We have made several measured collections across the Mullen Creek - Nash Fork shear zone in the region shown in Figure 1. The section described here was collected in the Medicine Peak Quartzite, east of South French Creek, across the shear zone into a quartz-feldspar gneiss east of the shear zone, from point A to point B of Figure 1.

The quartz-feldspar gneiss outcrops southeast of the shear zone. In samples collected across the eastern half of the shear zone, the gneiss grades into a augen gneiss, and eventually into a layered cataclastite. Houston (1968) reports that the layered cataclastic gneiss grades into a mylonite which resembles a fine-grained quartzite. However, the gneiss in the collection described here has not been mylonitized.

Figure 2 shows a series of photomicrographs of the gneiss progressing into the shear zone. Figure 2A shows the gneiss from the easternmost exposure of the shear zone, along line A-B of Figure 1. The rock consists of 40-45% potassium feldspar and plagioclase, 40-50% quartz and 5-10% muscovite. The quartz grains, in some samples, form discontinuous layers. There is evidence of granulation of the rock,

particularly along the grain boundaries of the feldspars. The general texture of the rock is one of large feldspar and quartz grains (0.5 to 1.0 mm) and discontinuous bands of quartz with minor regions between grains consisting of granulated feldspars, quartz and muscovite. The large quartz grains show undulatory extinction. The plagioclase is often partially altered.

Further into the shear zone there is more granulation evident along grain boundaries. The quartz grains show elongation in a preferred direction, however, the feldspars tend not to be elongated. The overall texture of the gneiss, several hundred meters into the shear zone, is one of large relict quartz and feldspar grains in a granulated matrix (Figure 2B). Eventually banding becomes pronounced in the gneiss (Figure 2C). The bands generally consist of quartz grains which may be elongated and which have grown together along sutured grain boundaries. The quartz shows undulatory extinction. Between the quartz bands are layers consisting of relict feldspar grains, fine-grained recrystallized quartz, granulated feldspar, and muscovite. Houston (1968) reports that banding in the gneiss becomes finer towards the center of the shear zone and that the gneiss eventually becomes a fine-grained mylonite. However, in this region of the shear zone, the gneiss is not mylonitized.

The Medicine Peak Quartzite in the region east of South French Creek shows progressive deformation going into the shear zone from the westernmost exposure, point A of Figure 1. The quartzite in this region is very pure, with only minor amounts of kyanite and muscovite. The average grain size is on the order of 0.75 to 1.0 mm, with a very small proportion of smaller grains (~0.10 mm). Samples from the western margin of the shear zone are highly laminated. The quartz grains are almost all elongated, with axial ratios up to 7:1 (Figure 3A). Elongation of the quartz grains is irregular, with grain boundaries completely sutured. Despite the elongation of the quartz grains, the undulatory extinction is relatively weak, with many grains showing no undulatory extinction. The style of deformation of the Medicine Peak Quartzite differs from that observed in the Basal Quartzite unit at the Stack of Glencoul in Scotland in which relict quartz grains became symmetrically elongated with a generation of new, dynamically recrystallized grains formed along serrated grain boundaries (Figure 3B).

In samples of the Medicine Peak Quartzite collected approximately one hundred meters into the shear zone, the average grain size of the quartz has decreased to approximately 0.5 mm. The relict grains are generally equant, with few grains showing any preferred elongation (Figure 3C). The undulatory extinction of the quartz is more intense than in samples from the margin of the shear zone. An increase in the percentage of small quartz grains is observed in these samples. Formation of the generation of small, recrystallized grains in the Medicine Peak Quartzite probably occurs by a different process than occurred in the quartzite at the Stack of Glencoul (Weathers et al., 1979). In the quartzites from Scotland it appears that the relict quartz grains developed serrations or bulges along the grain boundaries that pinched off with increasing deformation to form new, small grains.

Recrystallization of the Medicine Peak Quartzite apparently takes place by another process involving progressive rotation of subgrains to form new grains in the quartzite.

Near the center of the shear zone the quartzite consists primarily of equant grains, approximately 0.25 to 0.5 mm in size. The grain size is generally homogeneous, although a few larger, relict grains can be observed. The remaining larger grains may be elongated, with axial ratios of up to 6:1. Undulatory extinction is most intense in the quartzites from the center of the shear zone, often occurring in bands which extend across many grains (Figure 3D). Some of the quartzite shows evidence of a later, probably brittle deformation event in which the plastically deformed quartz grains are cross-cut by veins of small (10–50 micron) recrystallized or cataclastic grains (Figure 4).

Trends of progressive deformation towards the center of the Mullen Creek - Nash Fork shear zone have been observed in both the Medicine Peak Quartzite and the quartz-feldspar gneiss. Houston (1968) reported that the quartzite unit simply became more finely ground up at the center of the shear zone, implying a brittle deformation mechanism. Our investigation indicates that both the quartzite and the gneiss have been deformed plastically, with relatively minor, late brittle deformation.

DISLOCATION STRUCTURES

Dislocation structures in quartz grains from the Medicine Peak Quartzite and the quartz-feldspar gneiss units along the Mullen Creek - Nash Fork shear zone were studied using a JEM 200 kV transmission electron microscope. The dislocation densities were counted using the surface intersection method. The free dislocation densities were found to vary by a factor of about three across the width of the shear zone. This variation is in contrast to our previous study of deformation-induced microstructures across the Moine thrust in which the dislocation densities were found to be approximately uniform across the fault (Weathers et al., 1979).

Figures 5 through 7 show a series of electron micrographs taken of samples collected across the shear zone from point A to point B of Figure 1. The collection of samples was made on an oblique line across the shear zone; reported distances have been corrected to a perpendicular line across the shear zone. Figure 5 shows several electron micrographs from samples of the Medicine Peak Quartzite at the westernmost exposure of the shear zone. These samples show relatively high free dislocation densities, ranging from 10 to $13 \times 10^8/\text{cm}^2$. The free dislocations are generally homogeneously distributed throughout the samples; no dislocation tangles were observed. The dislocation networks and low-angle boundaries indicate that some dislocation climb has occurred, however, overall, there are relatively few subgrains in samples from the western margin of the shear zone. The dislocation structures observed in quartz grains from

the gneiss at the eastern margin of the shear zone are similar to those observed in the quartzite from the western margin. The free dislocation densities were also similar, on the order of $10^9/\text{cm}^2$.

Further into the shear zone, away from the margins, the quartz grains in both the quartzite and gneiss show lower free dislocation densities, on the order of 3 to $6 \times 10^8/\text{cm}^2$. The extensive development of low-angle boundaries in the samples indicate that a significant amount of dislocation climb has occurred (Figure 6). Many more subgrains were observed in samples away from the margins of the shear zone than in the samples collected at the margins. Figure 6C shows a region of extensive subgrain development in a quartzite collected approximately 100 m from the western margin of the shear zone. The subgrain sizes range from approximately 3 to 10 microns. Figure 6D shows the free dislocation density within one of the subgrains of Figure 6C. The free dislocation density of this samples is approximately $6 \times 10^8/\text{cm}^2$.

Figure 7 shows typical dislocation densities in samples collected near the center of the shear zone. The dislocation densities are low, on the order of $3 \times 10^8/\text{cm}^2$. Quartz grains from the quartzite and gneiss samples near the center of the shear zone have similar dislocation structures and free dislocation densities.

DISCUSSION

Figure 8 shows the trend of dislocation densities measured in samples collected across the Mullen Creek - Nash Fork shear zone. Quartzites from the westernmost exposure of the shear zone, point A of Figure 1, have free dislocation densities of 10 to $13 \times 10^8/\text{cm}^2$, corresponding to a differential stress of approximately 2 kbar. Quartz grains in the gneiss collected from the eastern margin of the shear zone have similar high free dislocation densities, on the order of $10^9/\text{cm}^2$.

Further into the shear zone, the free dislocation densities decrease in both the quartzites and in quartz grains in the gneiss. Dislocation densities in samples collected less than 100 m into the shear zone from the western margin and approximately 200 m into the shear zone from the eastern margin are on the order of 5 to $7 \times 10^8/\text{cm}^2$, indicating a paleo-differential stress of approximately 1.5 kbar. The free dislocation density is as low as 3 to $4 \times 10^8/\text{cm}^2$ at the center of the shear zone. The dislocation density at the center of the shear zone corresponds to a differential stress of about a kilobar. Samples from within the shear zone have lower free dislocation densities than samples from the margins of the shear zone, and they are also characterized *my* more extensive subgrain development, as seen in Figure 6C.

We have observed, petrographically, a trend in the microstructures of the quartzite and the gneiss indicating progressively increasing deformation going towards the center of the shear zone. The increasing deformation results in the development of a very finely banded gneiss,

and in an increase of small, recrystallized grains and more intense undulatory extinction in the quartzite. This trend of increasing deformation is in contrast to the decreasing free dislocation densities in both the quartzite and gneiss going into the shear zone.

The explanation of these two apparently contradictory trends of increasing deformation and decreasing paleo-differential stress levels, or decreasing dislocation densities, towards the center of the shear zone has not been resolved. One possibility is that the lower dislocation densities in the center of the shear zone have resulted from an annealing event. The extensive development of subgrains in samples away from the margins of the shear zone may have resulted from annealing, since during an annealing or heating event the free dislocations would organize themselves into low-angle boundaries and would form subgrains. The free dislocation density would then be considerably lower than in unannealed samples. Low dislocation densities and extensive subgrain development, such as shown in Figure 6C, characterize the results of our initial annealing experiments on naturally deformed quartzites.

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- Figure 1. Photomicrograph of the western margin of the shear zone, showing a foliation of quartz grains and the lack of dynamically recrystallized grains along the quartz-quartz grain boundaries. Average grain size is 0.75 to 1.0 mm. Figure 2B. Photomicrograph of the basal shear zone, showing greater elongation of relic quartz grains and the development of recrystallized grains along grain boundaries. Figure 3C. The Medicine Peak Quartzite shows several features which are typical of the shear zone. The average grain size is approximately 0.5 mm. The grains are generally equiaxed, not elongated as the grains from the margin of the shear zone. Figure 3D. The Medicine Peak Quartzite from the center of the shear zone. The rock consists of small, equiaxed quartz grains. Dislocation extinction is most intense in the center of the shear zone.
- Figure 4. A sample of quartzite showing a later, brittle episode of deformation in which veins of very small quartz grains (black) ruptured the larger, statically deformed matrix.
- Figure 5. Photomicrograph of the Medicine Peak Quartzite; sample collected from the western margin of the shear zone. The micrograph shows the typical dislocation structures and high dislocation densities. Note lack of dislocation tangles.
- Figure 6. Photomicrograph of a sample of quartzite collected approximately 100 meters into the shear zone. The dislocation densities are lower than in Figure 5. Figure 6C shows an area of extinction and high dislocation density. The dislocation density from 3 to 10 microns from the center of the shear zone is shown in Figure 6D. The dislocation structures are densely distributed in the center of the shear zone.

FIGURE CAPTIONS

Figure 1. Location map showing the Mullen Creek - Nash Fork shear zone (from Houston, 1968). The shear zone (wavy line pattern) cuts through Precambrian quartz-feldspar gneiss (qfgn), cataclastic migmatite and gneiss (cagn), metasediments (ms), and olivine gabbro (og). Our collection was made along line A-B, from the Medicine Peak Quartzite (mpq) into the quartz-feldspar gneiss.

Figure 2. Photomicrographs of the quartz-feldspar gneiss from the Mullen Creek - Nash Fork shear zone. Figure 2A. Gneiss from the eastern margin of the shear zone, point B of Figure 1. Figure 2B. Gneiss sample taken several hundred meters west of point B, Figure 1. The quartz grains (qtz) have become somewhat elongated. Figure 2C. Gneiss from near the center of the shear zone showing bands of quartz grains (qtz). Regions between quartz bands consist of granulated feldspar and micas. Bar scales = **0.5 mm**

Figure 3. Deformation of the Medicine Peak Quartzite. Figure 3A. A quartzite sample from the western margin of the shear zone, point B of Figure 1. Note elongation of quartz grains and the lack of dynamically recrystallized grains along the quartz-quartz grain boundaries. Average grain size is **0.75** to 1.0 mm. Figure 3B. Photomicrograph of the Basal Quartzite, Stack of Glencoul, Scotland. Note the difference in style of deformation, including greater elongation of relict quartz grains and the development of recrystallized grains along grain boundaries of the relict quartz. Figure 3C. The Medicine Peak Quartzite several hundred meters into the shear zone. The average grain size is approximately **0.5 mm**. The grains are generally equant, not elongated as are those from the margin of the shear zone. Figure 3D. The Medicine Peak Quartzite from the center of the shear zone. The rock consists of small, equant quartz grains. Undulatory extinction is most intense in samples from the center of the shear zone. Bar scales = **0.5 mm**

Figure 4. A sample of quartzite showing a later, brittle episode of deformation in which veins of very small quartz grains (black) ruptured the larger, plastically deformed quartz. Bar scale = **0.5 mm**

Figure 5. Electron micrographs of the Medicine Peak Quartzite; samples collected from the western margin of the shear zone. The micrographs show the typical dislocation structures and high dislocation densities. Note lack of dislocation tangles.

Figure 6. Electron micrographs of a sample of quartzite collected approximately 100 meters into the shear zone. The dislocation densities are lower than in Figure 5. Figure 6C shows an area of extensive subgrain development. Sizes of the subgrains range from 3 to 10 microns. Figure 6D shows the dislocation structures and density within one of the subgrains of Figure 6C.

Figure 7. Electron micrographs of a sample of quartzite collected near the center of the shear zone. Dislocation densities are low, on the order of $3 \times 10^8/\text{cm}^2$.

Figure 8. A plot showing the variation in dislocation density in quartz grains from samples across the Mullen Creek - Nash Fork shear zone, from point A to point B of Figure 1. (The western margin of the shear zone is plotted at 0 on the graph; the eastern margin is the point at 1400 meters). The dislocation density is highest at the margins, ranging from 10 to $13 \times 10^8/\text{cm}^2$, and decreases to 3 to $6 \times 10^8/\text{cm}^2$ towards the center of the shear zone. This trend may indicate that the samples near the center of the shear zone have undergone some post-deformational annealing.

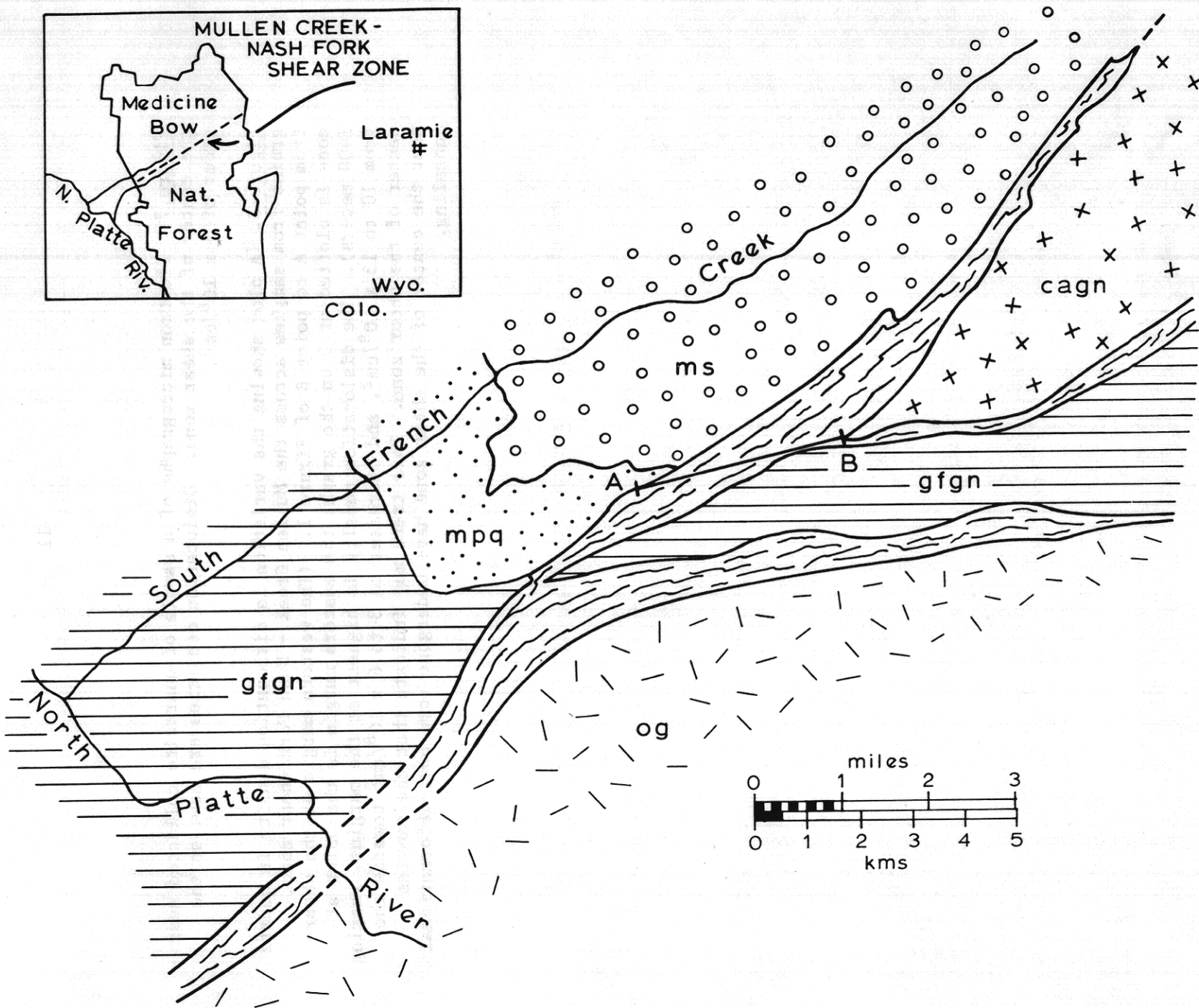
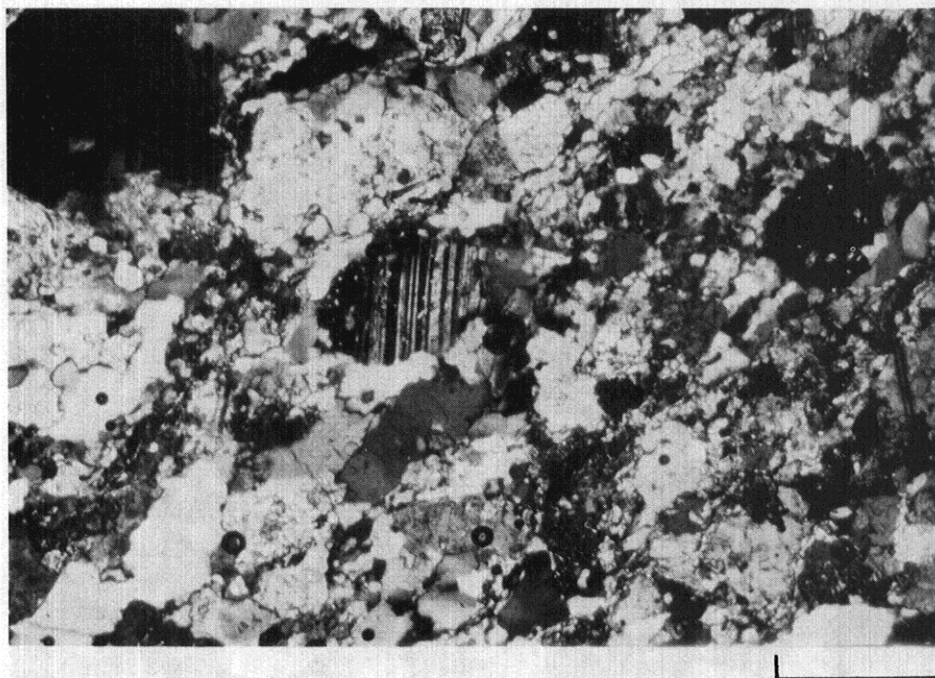


Figure 1

2A



2B

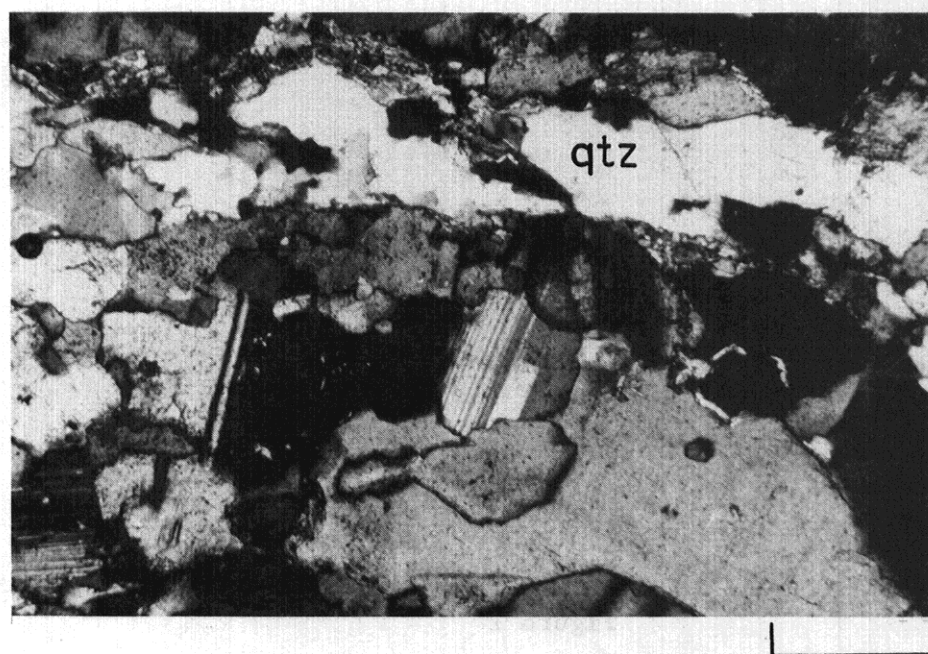


Figure 2

2C

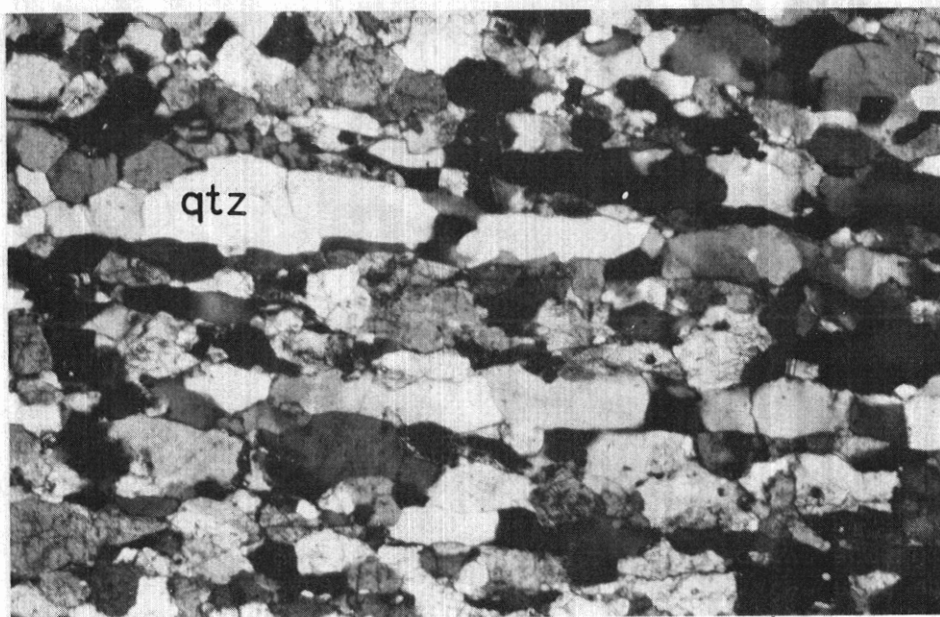


Figure 2

3A



3B

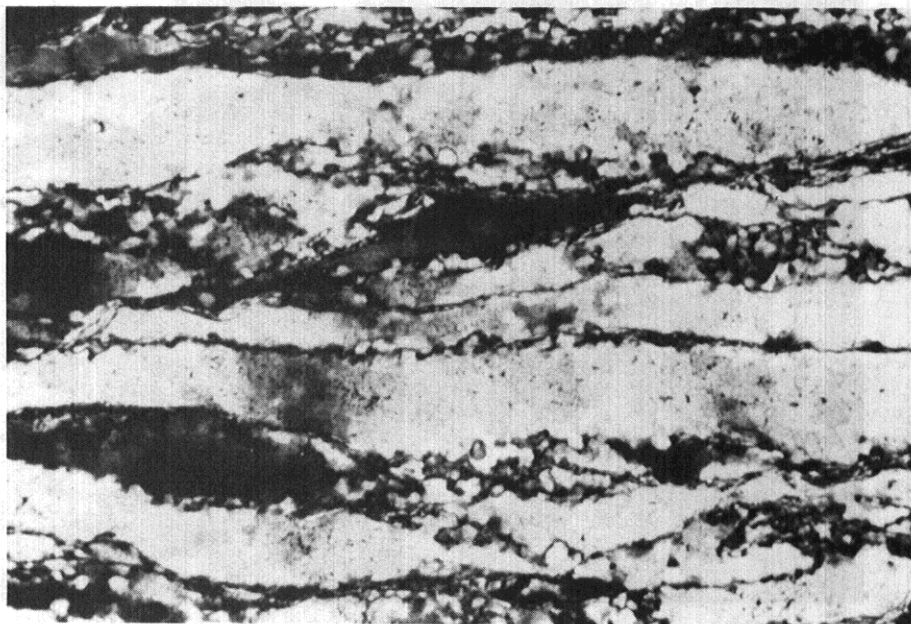
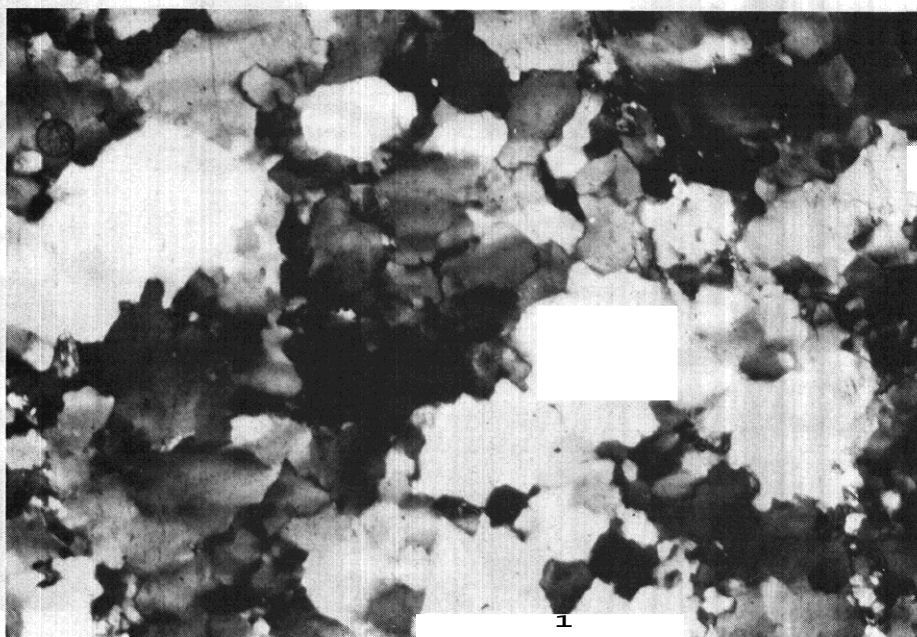


Figure 3

3c



3D

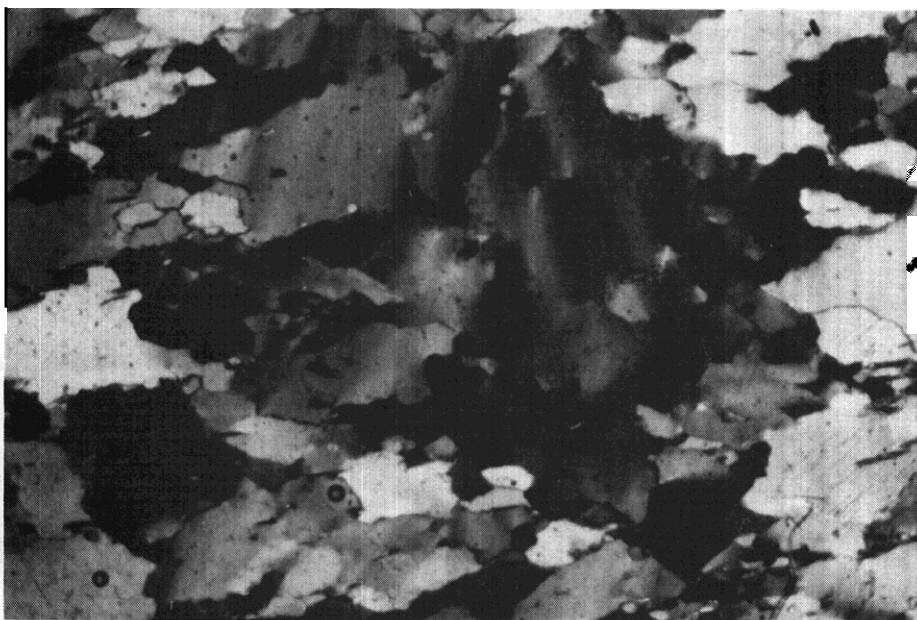
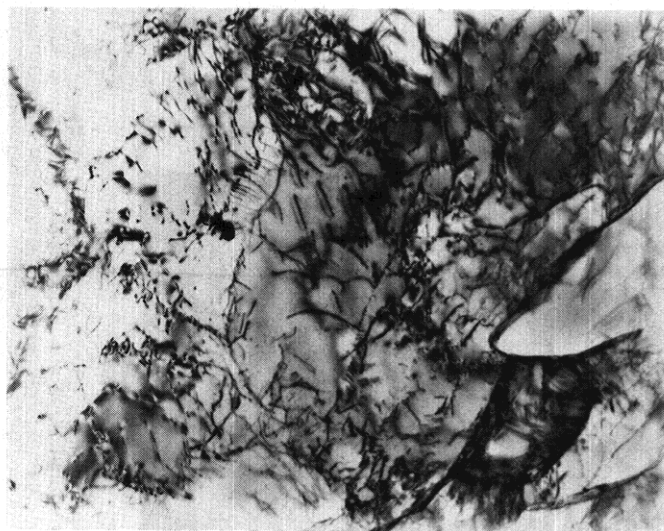


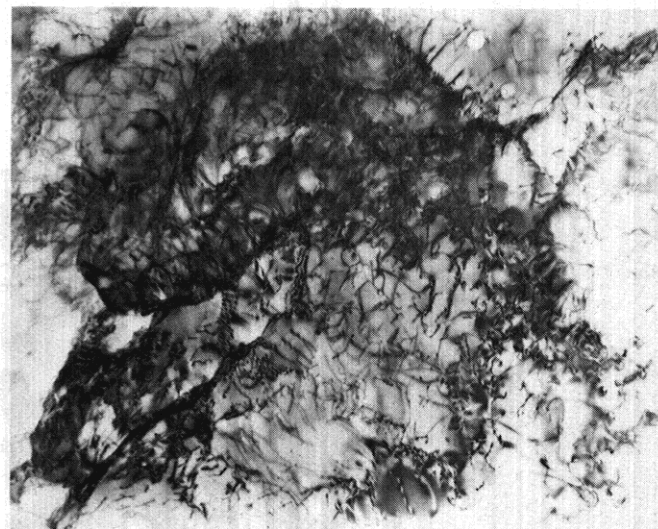
Figure 3



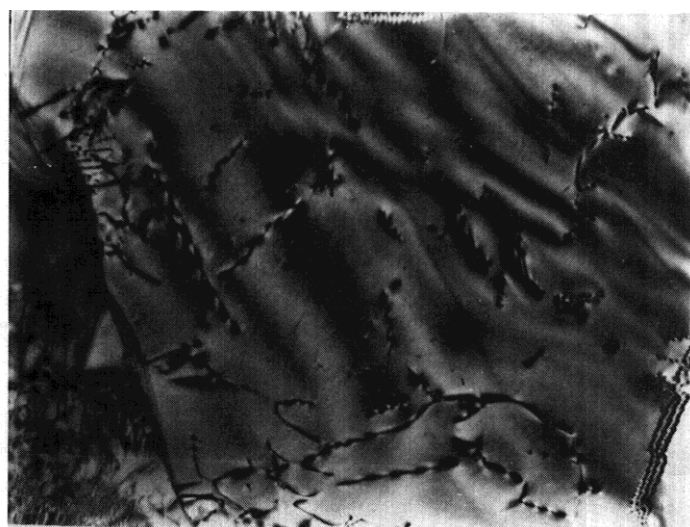
Figure 4



5A 11,000x



5B 11,000x

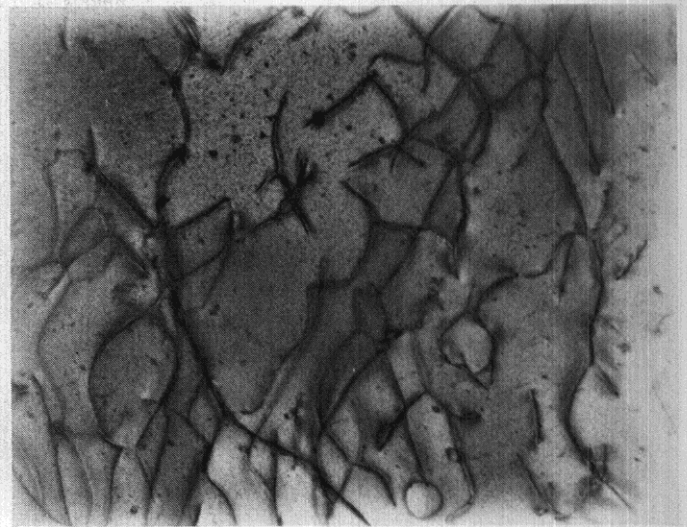


5c 34,000x

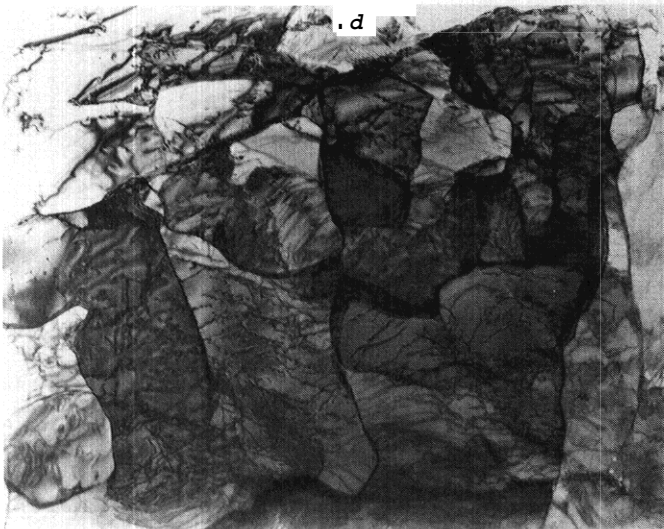
Figure 5



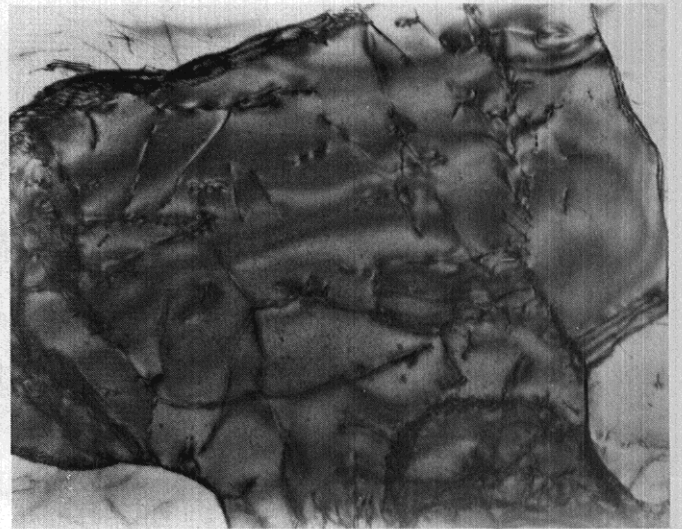
6A 9,400x



6B 14,000x

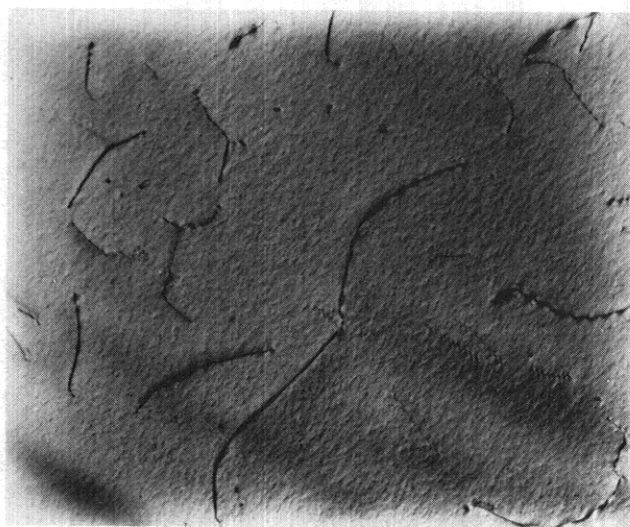


6C 3,450x

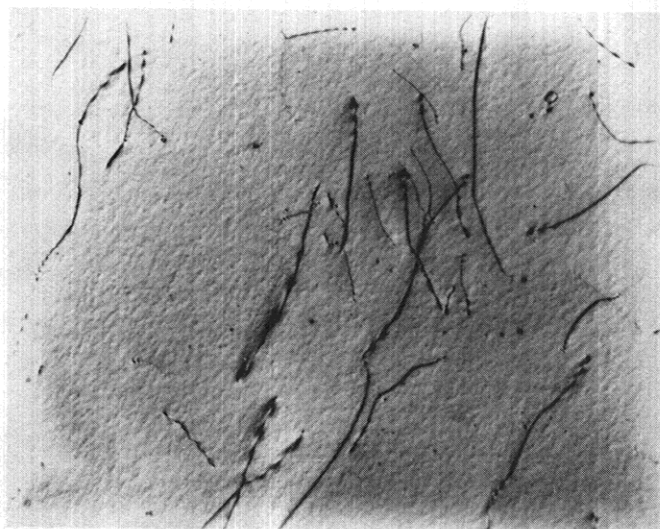


6D 14,500x

Figure 6



7A 22,000x



7B 22,000x

Figure 7

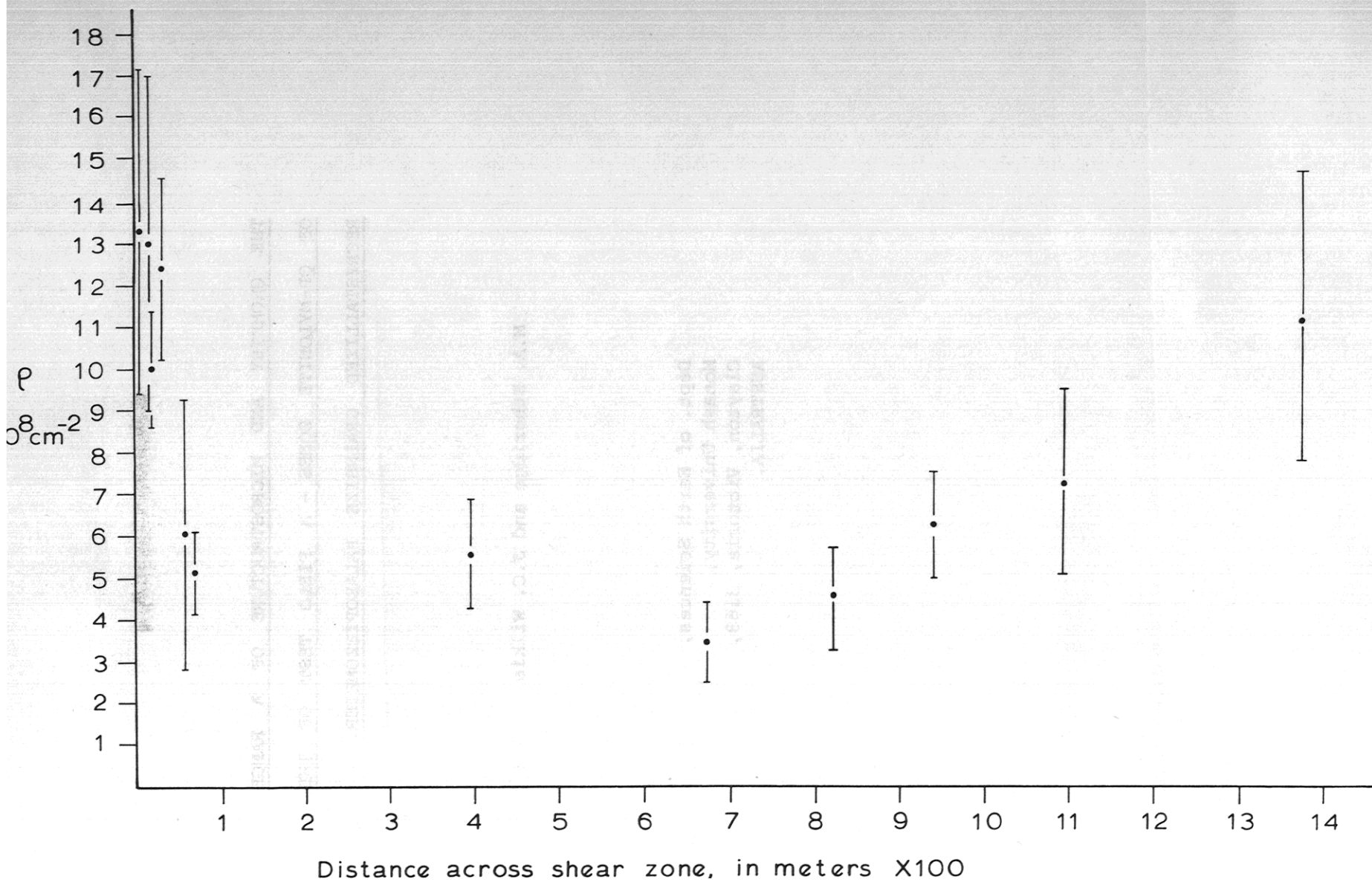


Figure 8
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